EFFICIENCY DIFFERENCES OF UPPER AND LOWER INJECTORS AND SCAN OF TAILRACE TEMPERATURE DISTRIBUTIONS

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Abstract

This paper addresses two aspects of thermodynamic efficiency measurements on Pelton turbines. On the one hand the results of measurements in the HPP of Sedrun, Soazza and Rabiusa-Realta which all are equipped with two jet horizontal Pelton turbines are presented. For these three plants the differences between upper and lower injector efficiencies for one and two nozzle operation are discussed. In all plants the upper injector showed lower efficiencies. For one nozzle operation differences of efficiency were observed which reached from 0.5% in the best and up to 1.5% in the worst case.

On the other hand a detailed study of the temperature distribution at the tailrace of the HPP of Linth-Limmern is presented and discussed with respect to efficiency. Temperature scans showed important vertical and horizontal temperature variation in the measuring section, because the measuring section was only two runner diameter downstream of the turbine. The use of three temperature sensors on a carefully selected elevation above the tailrace ground reduced the uncertainty of the measurement and enabled high repeatability of the results.

1 Thermodynamic efficiency measurements

Two aspects of thermodynamic efficiency measurements on Pelton turbines are addressed in the following. On the one hand the focus is on efficiency differences of the upper and lower nozzle for horizontal two jet turbines. This has been investigated for three different turbines in the HPP of Sedrun, Soazza, and Rabiusa-Realta. On the other hand a detailed study of the temperature distribution at the tailrace of the HPP of Linth-Limmern is presented and discussed with respect to efficiency.
All measurements were performed using the direct method in agreement with IEC 60041 section 14 [1], except where otherwise stated.

The turbine efficiency is defined as follows

$$\eta_{Tu} = \eta_{hyd} \cdot \eta_m = \eta_{hyd} \cdot \frac{P_{Tu}}{P_m} \tag{1}$$

where P_{Tu} is the mechanical power of the machine and P_m is the mechanical power of the runner and η_{hyd} the hydraulic efficiency.

$$\eta_{hyd} = \frac{E_m}{E} \tag{2}$$

The specific hydraulic energy E is

$$E = \frac{p_1}{\bar{\rho}} + \frac{v_1^2}{2} \tag{3}$$

where p_1 is the measured hydrostatic pressure at the high pressure measuring section, v_1 is the average velocity in the inlet section.

The specific mechanical energy E_m is

$$E_m = \bar{a} \cdot (p_{abs11} - p_{abs20}) + \bar{c}_p \cdot (\vartheta_{11} - \vartheta_{20}) + \frac{v_{11}^2 - v_{20}^2}{2} + g \cdot (z_{11} - z_{20}) + \delta E_m \tag{4}$$

where p_{abs11} is the measured hydrostatic pressure in the measuring vessel (designed by LUASA) at the inlet, p_{abs20} is the ambient pressure (assumed for Pelton turbines), ϑ_{11} is the water temperature in the measuring vessel and ϑ_{20} the average of three local temperature measurements at the outlet, and v_{11} and v_{20} are the averaged velocities in the measuring sections.

The following corrective term were determined as defined in IEC 60041 section 14.2 [1]

$$\delta E_m = \delta E_{m\vartheta} + \delta E_{mG} + \delta E_{mU} \tag{5}$$

where $\delta E_{m\upsilon}$ is the corrective term for variation of temperature, δE_{mG} is the corrective term for heat exchange through the walls and δE_{mU} is the corrective term for heat exchange with the ambient air.

The types and disposition of instruments used for the thermodynamic efficiency measurements and the additional signals from the control system are summarized in Figure 1. The sampling rate of data acquisition was 0.5Hz and the duration of the measurements were chosen to cover an integral number of surge tank oscillations.
For the applications at HPP Sedrun, Soazza and Rabiusa-Realta the high pressure and thermodynamic measuring sections were installed consecutively on the upper and lower injector of the 2 nozzle horizontal Pelton turbines.
A special thermometer support with pipe frames for the open low pressure measuring section was designed for the application at HPP Linth-Limmern as shown in Figure 2. The support was lifted by crane and therefore a continuous variation of the thermometer levels in the tailrace was possible. The thermometers are thereby fixed rigidly on the pipe frame and are exposed to the main flow. Similar supports were applied for all measurements presented in this paper.

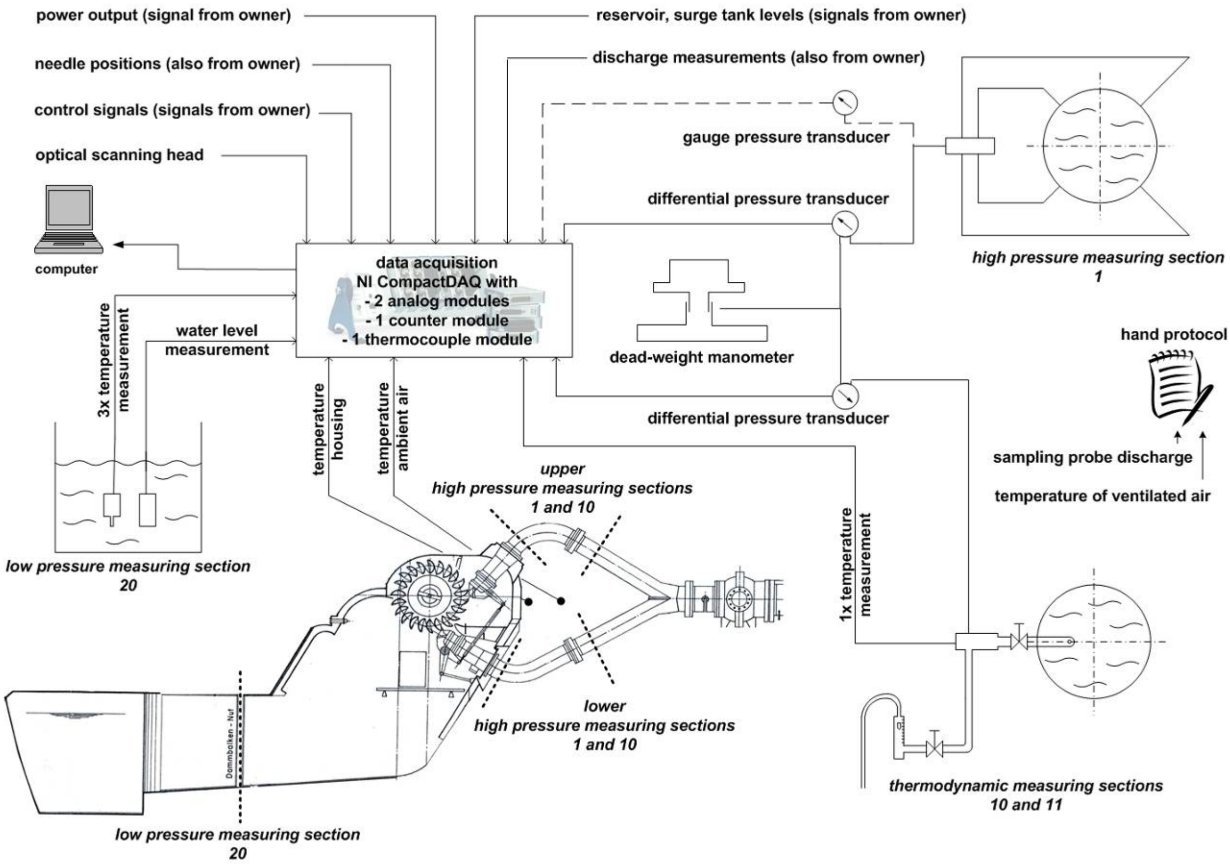

Fig. 1: Measurement arrangement and signal acquisition for thermodynamic efficiency tests

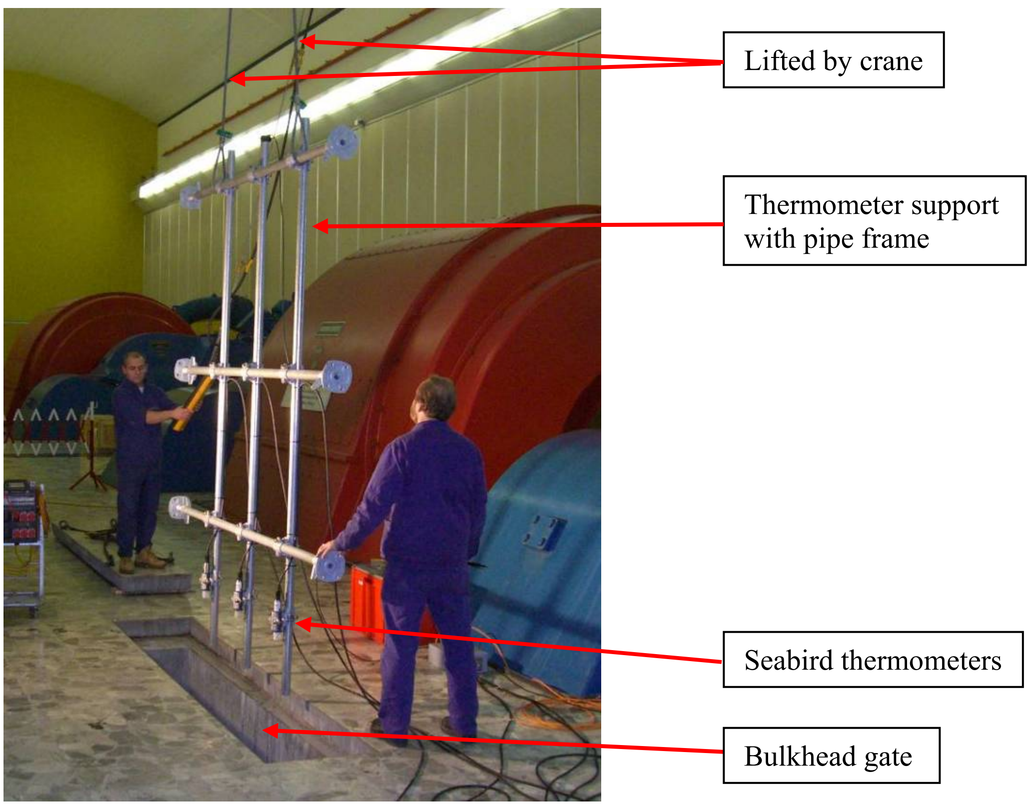

Fig. 2: Structure for measurement of water temperature in tailrace

2 Application at HPP Sedrun

6 Pelton turbines (3 Twin-Pelton machines) with horizontal shafts are installed in the hydro power plant of Sedrun of the Kraftwerke Vorderrhein AG, Switzerland. The technical specifications of each turbine are:

Name	Value
Rated power	25.8 MW
Rated discharge	5.1 m^3/s
Rated speed	428.6 rpm
Specified head	588.4 m
Turbine elevation	1315.26 m ASL
Runner diameter	2.150 m
Upper injector angle	100°
Lower injector angle	120°

Tab. 1: Specifications of each turbine

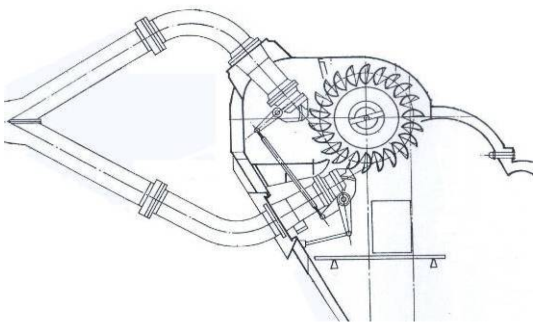

Fig. 3: Turbine layout at HPP Sedrun

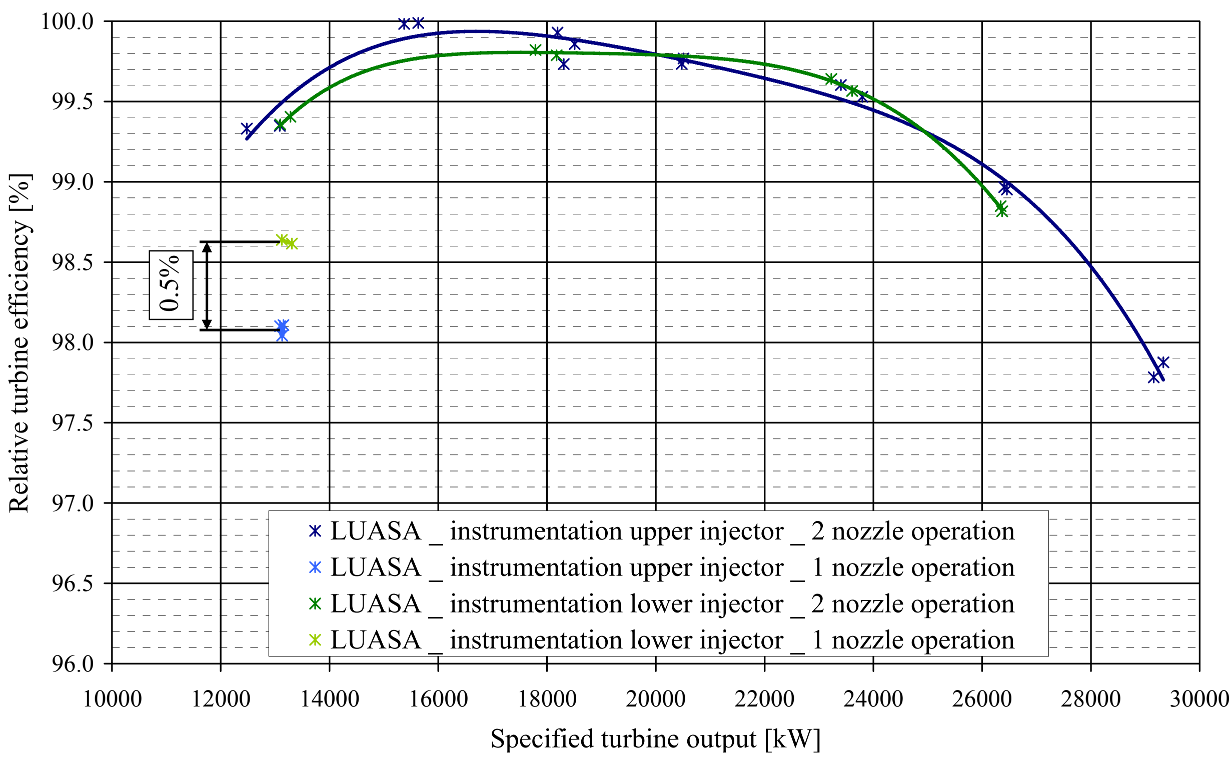

Fig. 4: Comparison of upper and lower injector efficiencies at 2 and 1 nozzle operation

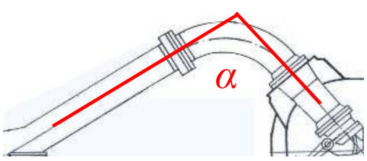

Fig. 5: Definition of the upper or lower injector angle (for specifications of each power plant)

In September 2006 thermodynamic efficiency measurements were carried out in the hydro power plant of Sedrun. The main results are (Abgottspon [3]):

- Measurements on the upper and lower injector in 2 nozzle operation do not show any systematic difference.
- Measurements on the upper and lower injector in 1 nozzle operation show a difference of about 0.5% in turbine efficiency as depicted in Figure 4. The bend to the upper injector is more curved by 20 degrees compared to the lower bend.

3 Application at HPP Soazza

2 Pelton turbines with horizontal shafts are installed in the hydro power plant of Soazza of the Misoxer Kraftwerke AG, Switzerland. The technical specifications of each turbine are:

Name	Value
Rated power	40 MW
Rated discharge	7.0 m^3/s
Rated speed	428 rpm
Specified head	704.0 m
Turbine elevation	482.41 m ASL
Runner diameter	2.410 m
Upper injector angle	105°
Lower injector angle	120°

Tab. 2: Specifications of each turbine

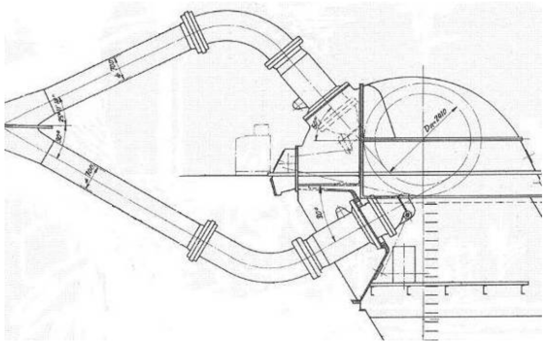

Fig. 6: Turbine layout at HPP Soazza

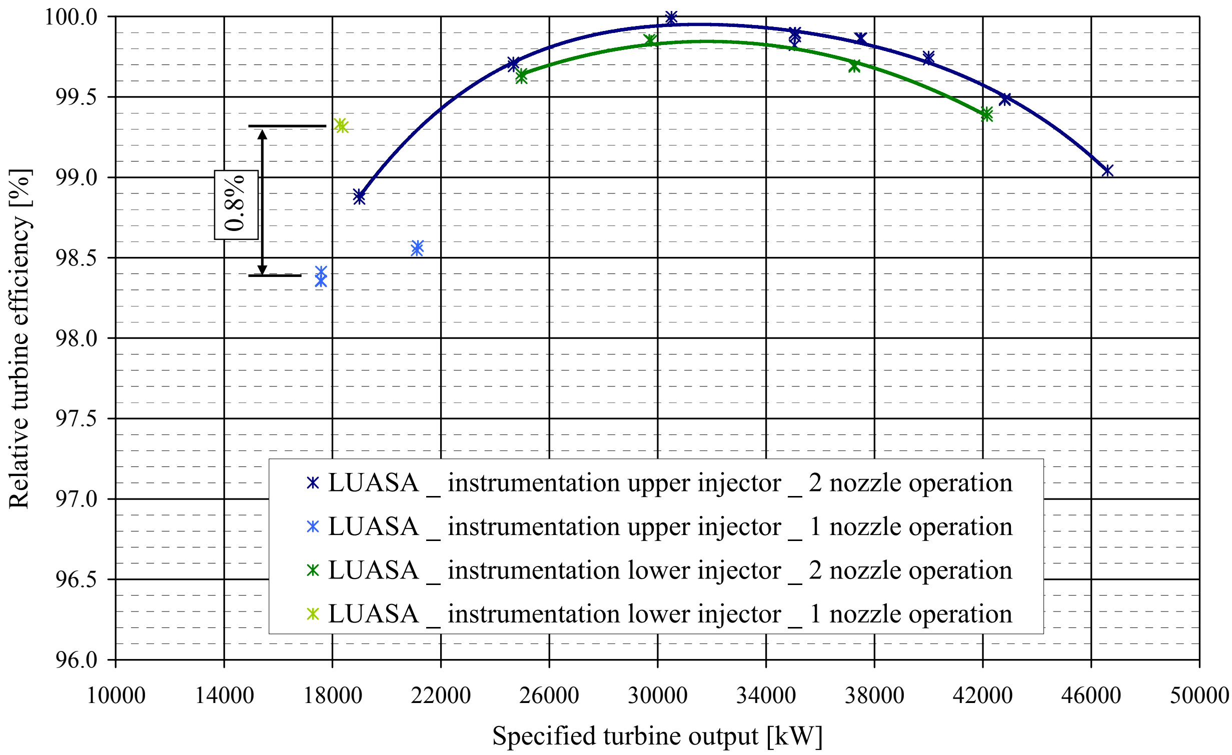

Fig. 7: Comparison of upper and lower injector efficiencies at 2 and 1 nozzle operation

In March 2007 thermodynamic efficiency measurements were carried out in the hydro power plant of Soazza. The main results are (Abgottspon [4]):

- Measurements on the upper and lower injector in 2 nozzle operation show a difference in the efficiency level of about 0.1%. This difference should be zero for identical flow conditions up to the measuring section identical losses for both branches and assuming that taping water for the upstream thermo measurements is representative for the upstream flow. This deviation lies well within the measuring uncertainty.
- Measurements on the upper and lower injector in 1 nozzle operation show a difference of about 0.8% in turbine efficiency as depicted in Figure 7. The bend to the upper injector is more curved by 15 degrees compared to the lower bend.

4 Application at HPP Rabiusa-Realta

2 Pelton turbines with horizontal shafts are installed in the hydro power plant of Rabiusa-Realta of the Kraftwerke Zervreila AG, Switzerland. The technical specifications of each turbine are:

Name	Value
Rated power	13 MW
Rated discharge	3.0 m^3/s
Rated speed	600 rpm
Specified head	498 m
Turbine elevation	621.25 m ASL
Runner diameter	1.420 m
Upper injector angle	112°
Lower injector angle	145°

Tab. 3: Specifications of each turbine

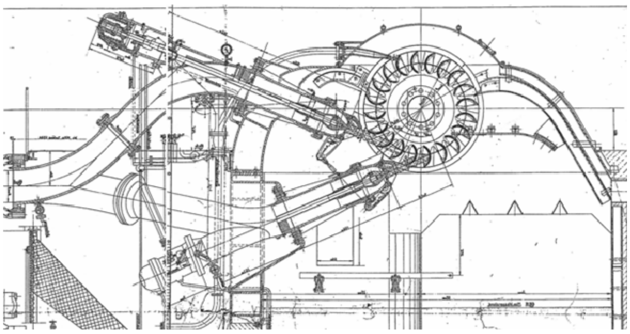

Fig. 8: Turbine layout at HPP Rabiusa-Realta

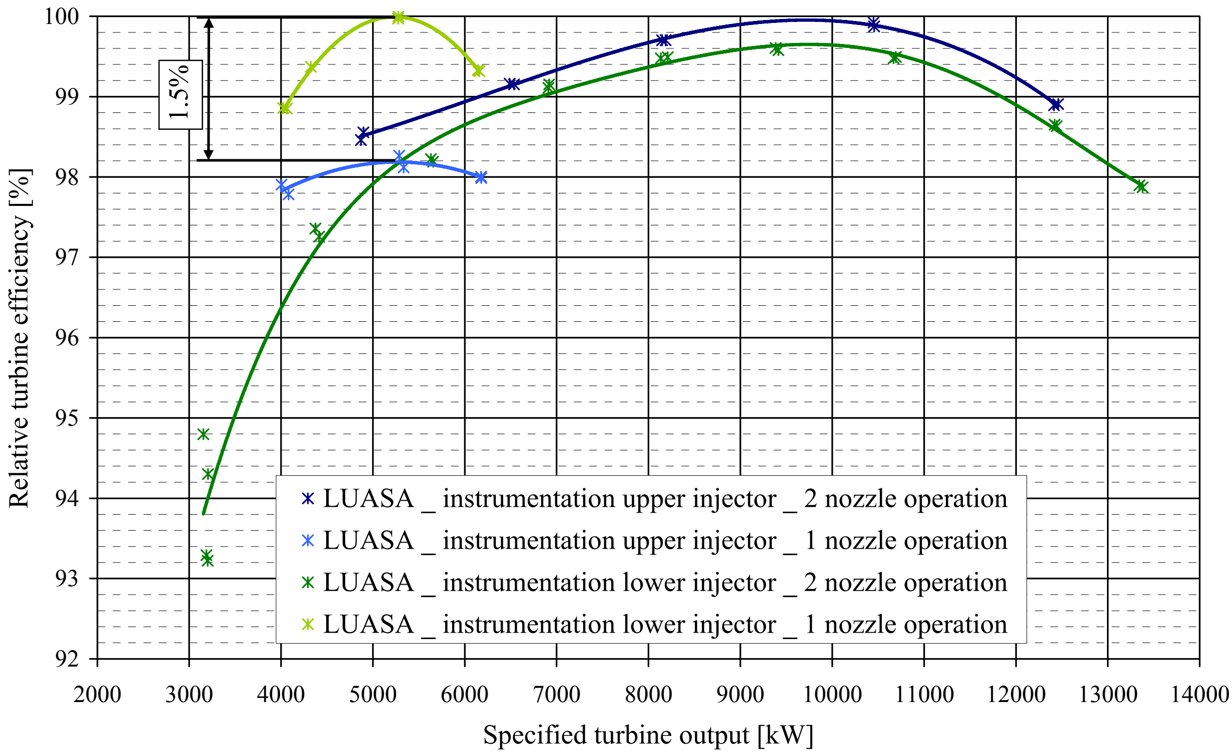

Fig. 9: Comparison of upper and lower injector efficiencies at 2 and 1 nozzle operation

The turbines of Rabiusa-Realta have an angle of 45degrees between the jets of the two injectors. This small angle may cause interference during the last phase of bucket emptying with the second jet. Thermodynamic efficiency measurements were carried in the hydro power plant of Rabiusa-Realta in November 2007. The main results are (Abgottspon [5]):

- Measurements on the upper and lower injector in 2 nozzle operation show a difference in the efficiency level of about 0.2%. This systematic difference could be a result of different energy and temperature distributions in the upper and lower measuring sections or be caused by different pressure losses from the bifurcation to the two measuring sections.
- Measurements on the upper and lower injector in 1 nozzle operation show a maximal difference of about 1.5% in turbine efficiency as depicted in Figure 9 being probably caused by adverse splashing water in the housing.
- The best efficiency point of the lower 1 nozzle operation is similar to the 2 nozzle operation measured on the upper injector.

5 Comparison between investigations of upper and lower injector efficiencies

The analysis of the 2 nozzle operations with the instrumentation on the upper and lower injector shows systematic differences for the HPP Soazza of 0.1% and for the HPP Rabiusa-Realta of 0.2%, as listed in Table 4. These systematic differences can have physical reason or be caused by measuring errors.

lower injector - upper injector

	angle difference [°] injector	efficiency difference [%] 2 nozzle operation	efficiency difference [%] 1 nozzle operation
SEDRUN	+ 20	-	+ 0.5
SOAZZA	+ 15	- 0.1	+ 0.8
RABIUSA-REALTA	+ 33	- 0.2	+ 1.5

Tab. 4: Comparison of injector efficiencies at 2 and 1 nozzle operation

The temperature measurements can be affected by the radial position of the sampling probe within the high pressure measuring section because uneven temperature and total pressure distributions may occur. The distance of the orifice from the sampling probe to the internal pipe wall was chosen to be within 0.1 – 0.15·D. The limit 0.05m from the internal wall given in IEC 60041, section 14.4.1.1 [1], was fulfilled.

Vinnogg [2] investigated the influence of the position of the sampling probe over a range of 0 – 0.25·D and observed total variations of less than ±0.07% of the average mechanical energy.

The determination of the head could also be different in the measuring section on the upper and lower injector. The uncertainty of hydrostatic pressure measurements is depending on the condition of the pressure taps and the distribution of the pressure over the cross section. To reduce such errors more than one pressure taps are recommended (IEC 60041, section 11.4.2 [1]). For Soazza 4 and for Rabiusa-Realta 2 pressure taps were instrumented in the high pressure sections. Generally, the influence of number of pressure taps with higher head becomes marginal. The different pressure losses upstream of the upper and lower injector measuring sections might also be reason for systematic differences. In future measurement the head difference between the upper and lower injector will be measured.

An uncertainty analysis for Rabiusa-Realta for head determination indicates variations of ±0.3m or ±0.05% in hydraulic efficiency. IEC 60041, section 14.7 [1] defines that the systematic uncertainty due to absence of exploration of energy distribution can amount to ±0.2% of the specific mechanical energy on the turbine high pressure side. All measured differences between the upper and lower injector measuring section of the above mentioned power plants indicate that assuming ±0.2% uncertainty for the inlet section is a reasonable quantity for an uncertainty estimation.

The first column in Table 4 shows the angle differences between the bends of lower and upper injector. The upper bend is more curved for all three HPP. It seems that there is a correlation between these angles and efficiency. The analysis of the 1 nozzle operations with the instrumentation on the upper and lower injector showed that all lower injectors have the better efficiency.

6 Scan of tailrace temperature at HPP Linth-Limmern

In the HPP Tierfehd of the Kraftwerke Linth-Limmern AG, Switzerland, 6 Pelton turbines (3 Twin-Pelton machines) with horizontal shafts are installed. The technical specifications of each turbine are:

Name	Value
Rated power	43.5 MW
Rated discharge	5.75 m^3/s
Rated speed	600 rpm
Specified head	969.89 m
Turbine elevation	817.21 m ASL
Runner diameter	2.030 m

Tab. 5: Specifications of each turbine

Fig. 10: Crane lifting the pipe frame within the bulkhead gate

Figure 11 shows the scan of tailrace temperatures for 3 Seabird thermometers as a function of the time and thermometer level above tailrace ground.

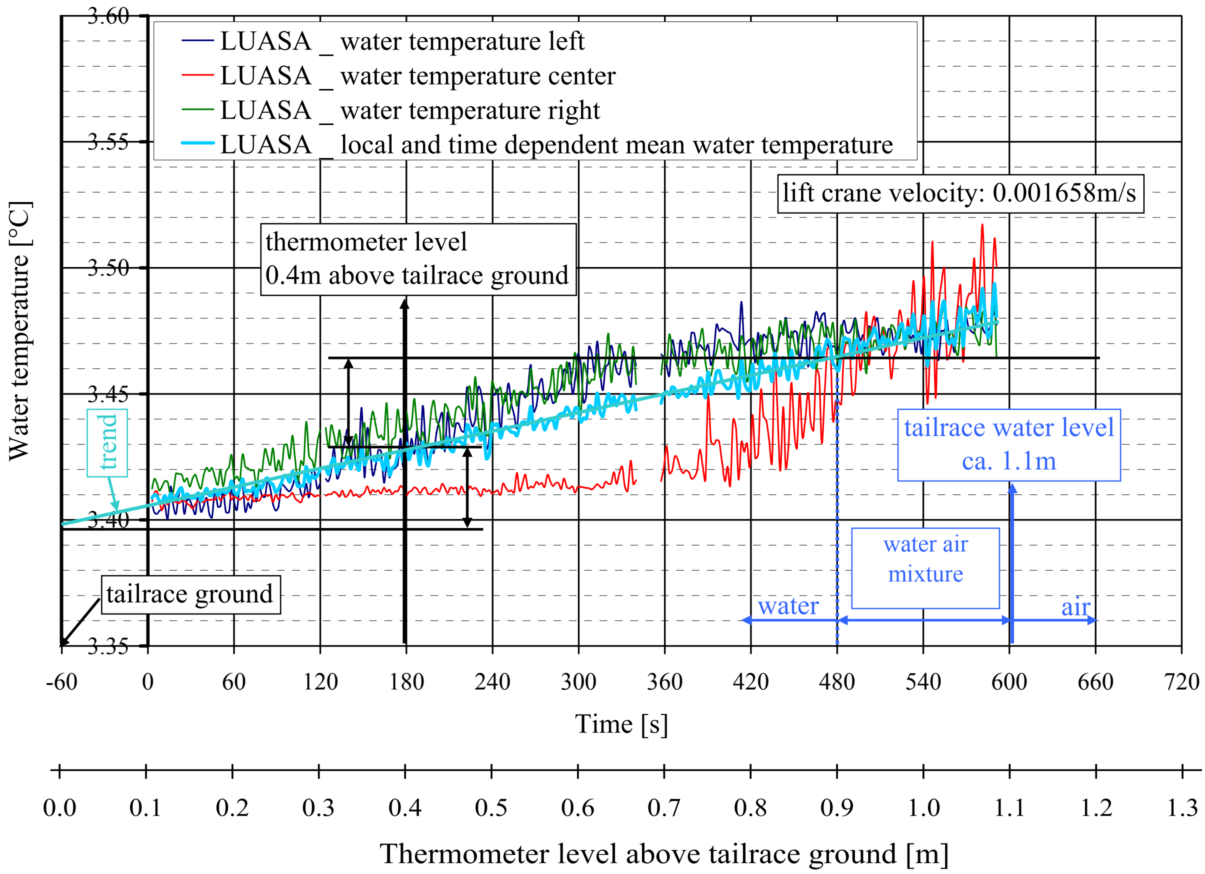

Fig. 11: Scan of tailrace temperature at HPP Linth-Limmern

The thermometer level was calculated from the defined lift crane velocity of 0.1m per 60 seconds. A total of 4 scans were conducted, two in November 2007 and two in February 2008. All 4 scans result in the same temperature distribution as the one shown in Figure 11. The sensors are positioned across the tailrace in such a way that each sensor covers an equal area. The sensors were fixed rigidly on the pipe frame, as shown in Figure 2. The distance from the low pressure measuring section to the runner is with 2·D well below the requirement of IEC 60041 section 14.5.1.2.1 [1].

The centre water temperature (red line) is lower than the right and left water temperatures up to an elevation of almost 1m. This indicates that the water falling down on the sides of the turbine housing is warmer than the rest of the water and that the mixing is not completed within this short distance from the runner. Temperature differences between the 3 sensors of up to 0.05°C were measured. In the best efficiency point for Linth-Limmern a temperature difference of about 0.19°C between the high and low pressure measuring section exists. If the centre temperature would not be used in the evaluation an efficiency reduction of about -0.7% would result.
The water surface is not well defined so close to the turbine, as can be seen in Figure 11. The upper zone consists of an air-water mixture, which was estimated to have a thickness of about 0.2m. The two black arrows in Figure 11 show the maximum temperature differences from the mean temperature.

7 Influence of averaged tailrace temperature on turbine efficiency

Figure 12 shows the relative turbine efficiency for steady state measurements as a function of the thermometer level above tailrace ground for the HPP Linth-Limmern. After the analysis of preliminary tests with measurements on different levels, it was decided to mount the thermometers 0.4m above the tailrace ground for the following efficiency tests. The tests with the thermometers at different levels were repeated again in February 2008 and showed the same trends.

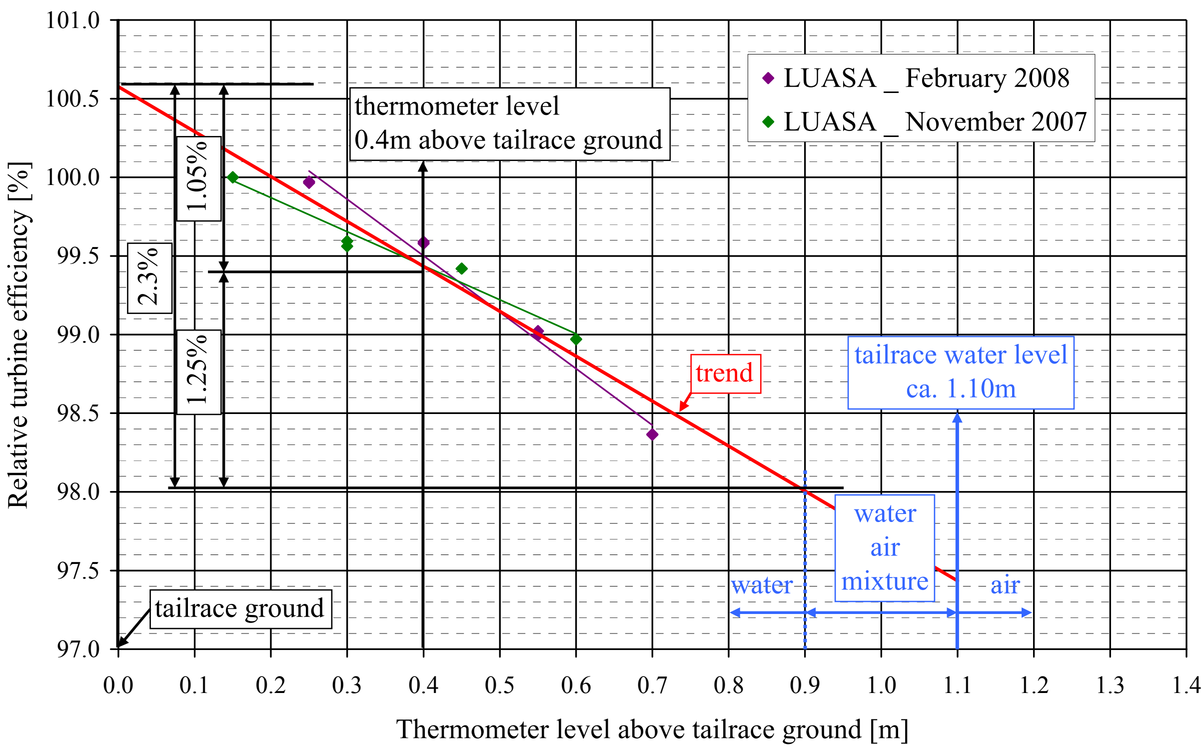

Fig. 12: Relative turbine efficiency influenced by the level of the thermometers

Because of the good repeatability of the temperature distribution measurements the results of measurements at an elevation of 0.4 m above the ground of the tailrace gave consistent and reliable results, but of course, due to this uneven temperature distribution the calculated measuring uncertainty increased
IEC 60041 section 14.5.1.2.1 [1] requires that the exploration of temperature variation across the measuring section shall be made in at least six points. If there is a difference of more than 1.5% between the efficiency values at any two locations additionally index tests are recommended.

Figure 13 shows the variation of the relative turbine efficiency as a function of the thermometer level for four different HPP measurements. Horizontally always three thermometers were averaged. The reference (100%) is the efficiency from the chosen thermometer position

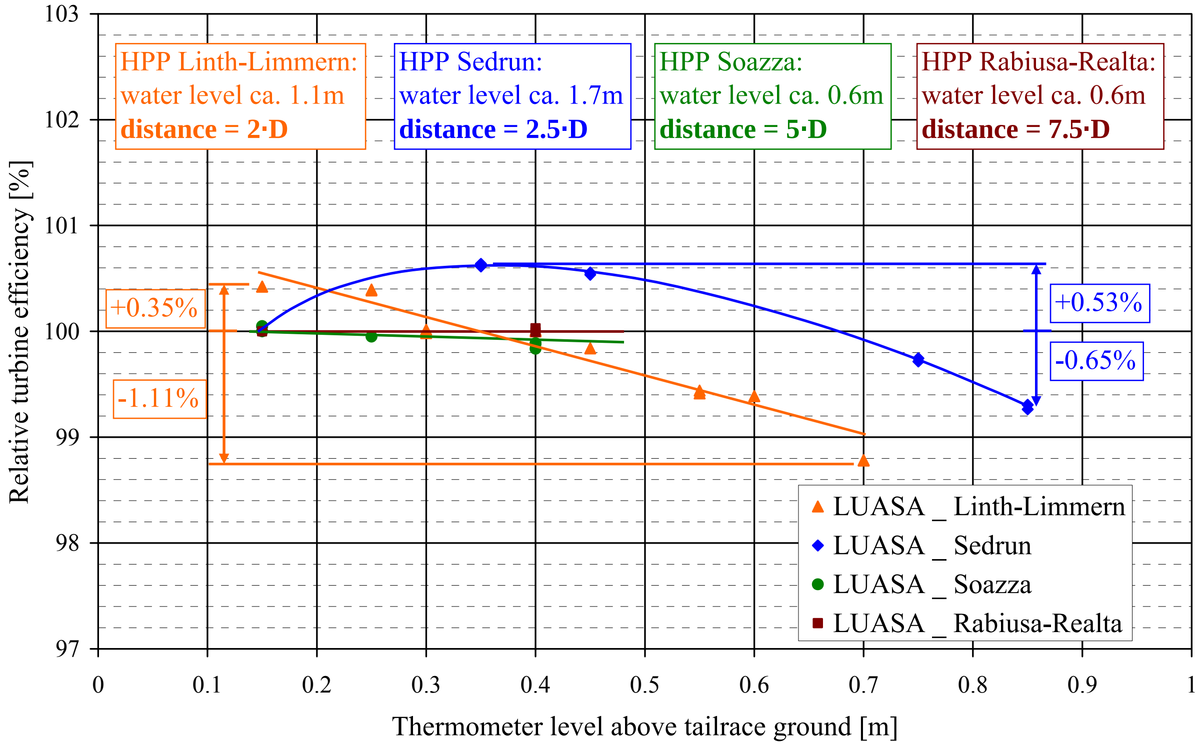

Fig. 13: Variation of relative turbine efficiency influenced by thermometer level for different HPP

IEC 60041, section 14.5.1.2.1 [1] defines that the measuring section with free surface at the low pressure side of a turbine must be located at such a distance from the runner that adequate mixing is ensured but no farer than necessary because of heat exchange with the surroundings. Distances from the runner of four to maximum ten runner diameters for impulse turbines have been found to be satisfactory.

The low pressure measuring section for the HPP Linth-Limmern was only 2·D away from the runner axis and thus adequate mixing is not ensured. The same was observed in the HPP Sedrun with measuring section 2.5·D away from turbine runner axis. The maximum differences in temperature lie still within the limits given by the IEC standard. The measurements in the other power plants with sufficient distance from the turbine and good mixing showed negligible influences of water temperature distributions.

For all measurements where measurements with sufficient distance from the turbine are not possible, a very careful survey of temperature distributions in the tailrace has to be performed.

8 Conclusion

On the example of three horizontal Pelton turbines with two jets differences between upper and lower injector efficiencies for one and two nozzle operations were analyzed. For one nozzle operation differences of efficiency were observed which reached from 0.5% in the best up to 1.5% in the worst case. For all investigated cases the upper injector showed lower efficiencies. This correlates with a more curved bend upstream of the upper injector in all cases. For two nozzle operation in two plants systematic differences in the results were found when instrumenting at the upper or lower injector. For clarification of these differences pressure difference measurements between the upper and lower taps are needed. In any case, the recorded differences are within the limits of ±0.2% uncertainty for the inlet section assumed in IEC 60041.

Temperature scans in the tailrace of the HPP Linth-Limmern showed important the vertical and horizontal temperature variation in the measuring section, because the measuring section was only two runner diameter downstream of the turbine. Measuring so close to the turbine contradicts the recommendations of IEC 60041 and needs a careful analysis of the influence of the temperature distribution on efficiency. A comparison with measurements in other plants where the recommendations of IEC 60041 with 4·D - 10·D distance was fulfilled showed that at these distances mixing leads to uniform temperature distributions. The use of three temperature sensors in the tailrace reduced the uncertainty and enabled high repeatability of the results.

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